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# ON RECENT INVESTIGATIONS & APPLICATIONS OF EXPLOSIVE AGENTS

## A LECTURE

DELIVERED TO THE MEMBERS OF THE BRITISH ASSOCIATION
AT EDINBURGH, AUGUST 1871

BY

Sir Frederick Augustus ABEL, F.R.S., Treas. C.S.

EDINBURGH
EDMONSTON AND DOUGLAS
1871

ON

# RECENT INVESTIGATIONS AND APPLICATIONS OF EXPLOSIVE AGENTS.

Rec'd 4-29-36 MEW

IN submitting to the Members of the British Association some account of recent progress made in the production and application of explosive agents, I cannot attempt to give much more than an outline of the nature and results of important investigations which have been instituted, and are still being pursued, relating to the development and regulation of the explosive force of gunpowder, and to the application of some other explosive materials, which are already supplanting gunpowder in several of its important uses.

The manufacture of gunpowder, required for war-purposes, was carried on here and abroad for very many years without any important modification. The system pursued in this country in effecting the incorporation of the ingredients, and in converting the mixture into granulated gunpowder, of sufficient density and hardness to enable it to resist injury by transport and storage in all climates, furnished a product which was greatly superior to the generality of foreign gunpowders in regard to its keeping qualities, but which was also more violent in its action, because, in fact, the conditions essential to a rapid and complete transformation of the several constituents were more thoroughly fulfilled in its manufacture; and which hence earned on the Continent the name of "poudre brutale."

The comparatively small charges used even with the heaviest cast-iron smooth-bore guns, which until recently constituted our most powerful armaments by sea and land, were, however, regarded in this country as not unduly trying to the endurance of those guns; and although, about fourteen years ago, some attention was directed to the question of modifying the form or proportions of heavy guns with a view to increase their durability, in consequence mainly of some very instructive experiments instituted in America by Major Rodman, it was not until some little time after the first great stride was made in the increase of power of our artillery (by the introduction of the 110-pounder Armstrong rifled wrought-iron gun), that attention became seriously directed to the importance of attempting to reduce the violence of action, or rapidity of explosion, of the gunpowder to be employed in the increased charges required to impart the requisite velocity and accuracy of flight to comparatively heavy projectiles. A comparison of the weight of shot and of the charges of powder used in the heavy guns of the present day, with those employed in the most formidable *cast-iron* siege and naval guns, will at once show how greatly the conditions must have become modified which attend the application of gunpowder to projectile purposes. Much has been written and said, especially of late, as to our having been far behind other nations in devoting attention to the modification of gunpowder, with a view to meet the altered conditions attending its application in the heavy guns of the present day; but the fact is, that not only were the first investigations into the action of fired gunpowder made in this country, but steps were also taken in England, almost as soon as in any other country, towards the production of a gunpowder, by employment of which the full powers of heavy guns may be developed with the least detriment to their durability.

In 1858 a small Committee was appointed to determine upon the best description of gunpowder to be used in the Enfield rifle, and not long afterwards this Committee was instructed to extend its inquiry to cannon powder—the most powerful gun of the service at that time being the 110-pounder Armstrong gun. One of the members, General (then Captain) Boxer, had, some few months previously, called attention officially to the desirability of modifying the action of the charges of powder used in the larger natures of guns, either by employing a weaker powder, or a larger grain and denser powder, the charge being increased in amount in order to obtain the same average pressure, and consequently the same initial velocity, as furnished by the quick powder then used. A careful consideration of the directions in which gunpowder was susceptible of modification, with a view to the reduction of the rapidity of its explosion, led the Committee to institute a series of experiments, which resulted, in the first instance, in the introduction into the service, in 1860, of the so-called rifle large-grain powder, for all rifled guns, and subsequently in the provisional introduction of pellet-powder for the heavier natures of ordnance. The means and appliances at the command of this Committee for carrying out their experimental investigations were small and imperfect; but the results at which they arrived not only served as the starting-points of the successful results attained by the present Committee on Explosive Substances, but also became known to and aroused the attention of Continental Powers, through the agency of officers who visited this country at about the time of the Exhibition of 1862, at which date pellet-powder had already been experimented with for some little time. In America experiments on gunpowder were vigorously pursued at the same time as they were being slowly carried on, with comparatively imperfect means, in England, and the particular form of powder known as Prismatic, the production of which was developed in Russia a few years ago, and which has been to some extent adopted in Prussia, appears to have been of American origin, though it has not found favour in that country, where a gunpowder similar in form and size to the new powder known as *Pebble* is employed in guns of large calibre, under the name of *Mammoth powder.*

The principles laid down by the first Committee on Gunpowder, in 1858, as their guide in attempting to reduce the violence of action of powder when fired in large charges, have been, up to the present time, adhered to by those since entrusted with the continuance of these investigations. Before specifying them it may be instructive to glance briefly at some ways in which gunpowder may readily be modified, with the object of increasing or diminishing the rapidity and violence of its explosion, and at the reasons why they have not hitherto been selected.

As gunpowder is simply an intimate mechanical mixture of a powerful oxidising agent—saltpetre or potassium-nitrate, with two readily-oxidisable substances, sulphur and carbon or charcoal—it is obvious that the behaviour of this mixture, *i.e.* the rapidity with which it will explode, and the nature of the results furnished by its explosion, are susceptible of great modification by variations in the proportions of its ingredients.

According to the long-accepted chemical theory of the action of gunpowder, the function of the charcoal was to undergo conversion into gas by partial or complete oxidisation (*i.e.* by conversion into carbonic acid or carbonic oxide), according to the proportion which it bears to the saltpetre employed, while the sulphur was considered to act in two ways—firstly, in promoting the ready ignition of gunpowder by reason of its great inflammability; secondly, by uniting with the potassium in the saltpetre, and thus rendering available the whole of the oxygen for the oxidation of the carbon.

That this view is, to say the least, only a very imperfect explanation of the action of the ingredients in gunpowder, has long since been demonstrated; but the broad facts are undoubted that the rapidity of explosion of a mixture of these three substances may readily be increased or diminished by modifications of the proportions of sulphur or charcoal, or of both, with which the saltpetre is mixed. A very notable difference may be observed in the rate at which two trains will burn, which consist of gunpowders in other respects alike, but differing, for example, in the proportion of charcoal which they contain.

A comparison of the composition of English and foreign gunpowders shows that some of them differ considerably from each other as regards the proportions of their ingredients; and there can be no doubt that these differences may exert a very decided influence upon the action of these gunpowders.

The extent to which the charcoal employed in their preparation has been burned (*i.e.* the duration of the carbonising process, or the temperature at which it has been effected), and its consequent composition, also vary considerably, and it has been abundantly demonstrated, by the more recent experiments conducted at Woolwich, that, the other characters of cannon powders, tried one against another, being alike, the violence of action increases in direct proportion to the amount of volatile constituents (as indicated by the proportions of hydrogen and oxygen) which have been allowed to remain in the charcoal. This result was observed many years ago in connection with powder for small arms, the French having found that a highly inflammable charcoal (*charbon roux*), produced by exposure of wood to a comparatively low temperature, furnished a very violent gunpowder, which, on account of its destructive action upon the firearm, was termed *poudre brisante.* It was, however, not known that apparently small differences in the composition, and consequently in the physical properties and ready inflammability of the charcoal, might be productive of very considerable differences in the action of gunpowder even when employed in large charges.

It need scarcely be pointed out, after what has been said regarding the influence exerted by certain variations of composition upon the rapidity of explosion and consequent violence of gunpowder, that different modifications in the composition of powder, which are opposed in the results they produce, may be made more or less completely to neutralise each other's effects. Thus, the reduction in rapidity of action of gunpowder, which may be effected by a diminution in the proportion of the inflammable ingredient sulphur, or of the oxidising ingredient saltpetre, may be counteracted by the employment of a slackly-burned and therefore highly inflammable charcoal; and in this way it may be possible that the composition hitherto fixed for gunpowder in this and some other countries may be susceptible of modification, with advantage in point of economy.

Sufficient has been said on this head to show that the explosive action of gunpowder is susceptible of very extensive modification by variation of its composition. But inasmuch as the force exerted by gunpowder is due not simply to the actual amount of gaseous products resulting from the explosion, but also, and in the largest proportion, to the heat developed by the chemical action, it follows that there must be particular proportions of ingredients which, leaving other conditions out of consideration, would appear the best, as furnishing the largest amount of gaseous matter compatible with the development of the highest temperature.

There can be no doubt that the proportions of saltpetre, sulphur, and carbon, fixed upon in the earlier days of gunpowder manufacture (and which have hitherto undergone no *very* considerable modification, and indeed *none* made with any definite design), were not fixed upon by any theoretical considerations, but were purely the result of tentative experiments; but they very nearly correspond to those required for the development of the most energetic action of the saltpetre upon the carbon (regarding the charcoal for a time as pure carbon), though they are not calculated to furnish the largest amount of gas from a given weight of the mixture. The latter result would necessitate the employment of the carbon in the proportion to produce carbon monoxide, or carbonic oxide; while the amount actually used in gunpowder is approximately that required to produce only carbon dioxide or carbonic acid, assuming the sulphur only to exercise the function above indicated, and not to take to itself any of the oxygen of the saltpetre. It has now been long established that the sulphur does at any rate undergo partial oxidation; but it is also admitted that the employment of the proportions of saltpetre, carbon, and sulphur, indicated by the old theory, which provided for the full oxidation, or conversion into carbonic acid, of the greater part of the carbon, furnished a mixture by the explosion of which a comparatively very great amount of chemical energy, and consequently of heat, is developed (or of pressure, when the charge is confined).

It is upon such considerations as these that the late Committee on Gunpowder came to the conclusion that, in attempting to moderate the explosive violence of gunpowder when used in large charges, it was inadvisable to make any change in the established composition of gunpowder which might be productive of a diminution of the total pressure developed by a charge, unless the desired results were unattainable by modifying the mechanical and physical characters of powder—in other words, by introducing changes in the *preparation* of gunpowder, and in the *form* in which it is employed. It required but few experiments to demonstrate that the rapidity of explosion of gunpowder was readily susceptible of great reduction by simple mechanical means, and hence those means have been adhered to by the present Committee on Explosive Substances, in elaborating the powder now manufactured for naval and siege guns.

The degree of perfection to which the ingredients of powder are prepared by grinding, and afterwards mixing or incorporating, affords an obvious means of modifying the rapidity of explosion of the mixture, but it would also evidently be both unphilosophical and unpractical to reduce the rapidity of burning of powder by diminishing the degree of completeness to which the ingredients would react upon each other, and thus employing them wastefully, which would be the case if they were not converted into as intimate a mixture as is attainable by known means and appliances. But, starting with as perfect a mixture as can be prepared of the ingredients in the proportions calculated to furnish the maximum attainable change of volume (and consequently of total pressure at the time of explosion), there are *five* different directions in which gunpowder may be modified as regards its physical and mechanical characters, and the means thereby presented of regulating the rapidity of explosion, have, up to the present time, proved quite sufficient for all requirements. These variable points are—*the size* of individual masses composing the charge of powder; *the form* of these masses, and the *mechanical condition* of their *exterior;* the *density* or compactness of the masses, and their *hardness*. The size and form of the masses are readily modified by moulding the mealed powder into forms of a particular size and shape, as in the case of pellet-powder, prismatic, cubical, or spherical powder; or by breaking up, to a greater or less extent, and in a symmetrical or irregular manner, cakes of compressed powder of different thicknesses, thus producing what is called granulated powder, which ranges in size from fine sporting powder to pebble powder. The surfaces of these masses may be left in their original rough condition, or they may be more or less smoothed and deprived of sharp angles and edges by means of attrition and subsequent glazing or coating with graphite; and their ready inflammability may be correspondingly reduced. The density or compactness of the powder is determined by the pressure to which the material is submitted when converted into slabs, pellets, or other forms; and the hardness is regulated by the proportion of moisture contained in the powder at the time that it is submitted to pressure.

Experience has shown that it requires a very careful adjustment of the several mechanical and physical characters of gunpowder to reduce the rapidity of its action, and at the same time to develop the requisite total pressure and consequent velocity with sufficient uniformity. The first promising results obtained by the late Committee on Gunpowder were simply arrived at by increasing the size of the masses composing the charge; subsequently it was found that the results were greatly improved by paying attention to the density and hardness of the powder, and by adopting measures to promote uniformity in regard to these properties of the powder-particles composing a charge, the importance of which has become more evident as the means available for examining the action of fired gunpowder have been extended and perfected.

A very brief examination only can be attempted of the results which have been arrived at by earlier experiments with regard to the pressure developed by exploding gunpowder, and of those quite recently obtained by the Government Committee on explosive agents.

Although the first attempt was made by a Frenchman, M. de la Hiri, in the beginning of last century, to explain the action of fired gunpowder, it was Robins who first investigated the subject experimentally, by carefully determining the quantity of gas generated by the explosion, and by endeavouring to estimate from experimental data the increase of elasticity of the gases due to the temperature developed by the explosion. He came to the conclusion that the permanent gases evolved from powder occupy about 240 times its volume, at normal temperature and pressure, and that the heat generated raised this volume to 1000 times that of the powder, causing the latter therefore to exert a force corresponding to a pressure of about 1000 atmospheres, or 6¾ tons on the square inch. The first experiments, of which the object was a direct determination of the pressure exerted by gunpowder when exploded in closed vessels, were made by Count Rumford in 1793, who confined a small charge of sporting powder (not more than 18 grains), in a very strong wrought-iron vessel, the opening of which was closed by means of a weight. The vessel or species of gun was supported vertically, and the charge was exploded by applying a red-hot ball to the lower extremity of the vessel, which formed a closed vent and was filled with powder. A given charge having been employed, the vessel was closed by a weight which was considered likely to be equivalent to the gaseous pressure to be developed. If this weight was raised by the explosion of the particular charge used, it was increased until it just resisted the force exerted by the explosion; this weight was then taken to represent the pressure exerted by the powder. The results obtained by Rumford were conflicting, but the conclusion arrived at by him was, that the central force developed by the explosion of gunpowder corresponded to 101,021 atmospheres, or a pressure of 662 tons upon the square inch. Rumford endeavoured to reconcile the development of this enormous total pressure with the fact that guns could endure it, by assuming that the explosion of powder takes place very gradually in a gun, being completed only when the shot leaves the bore.

Another method, first suggested by Colonel Cavalli in 1843, of determining the pressure in a gun's bore, consisted in inserting a number of small tubes or gun-barrels into the gun along its length; spherical bullets were inserted into these barrels, and the pressure at different parts of the gun was estimated by ascertaining the velocities by which these balls were propelled when the gun was fired. An improved form of the same method of experiment was adopted in 1854, by the Prussian Ordnance Committee, but was only applied to guns of small calibre. It consisted in fitting a small gun-barrel into a hole drilled into the powder-chamber of the gun; after the gun was loaded, a cylinder, having the same longitudinal section as that of the projectile in the gun, was inserted into the small barrel. Assuming the pressure in the powder-chamber to be uniform throughout, the cylinder and the shot would travel through equal spaces in the same time, and the cylinder, after having travelled eight inches, would be out of the sphere of action of the gas. If the cylinder had a longitudinal section one-half that of the shot, it would require double the velocity, and so on; and thus, by knowing the relation of the longitudinal section of the cylinder to that of the projectile, the velocity of the latter, after it had prescribed a particular distance, could be ascertained by determining that of the cylinder.

The results of the Prussian experiments indicated that the maximum pressure in a 6-pounder gun is 1100 atmospheres, and in a twelve-pounder 1300 atmospheres. The same method subsequently applied to a 70-pounder rifled gun appears to have given an indication of a pressure of about 3000 atmospheres.

Some very interesting experiments were instituted in the United States, in 1857, 8, and 9, by Major Rodman, who registered the pressures exerted in a gun on the explosion of a charge, by means of a ingenious instrument, well known as Rodman's Pressure Piston, which has since been extensively employed in similar experiments in France, Prussia, and other countries. To ascertain the pressure exerted in any portion of the gun's bore, Major Rodman drilled a hole in the gun at that part, and inserted a hollow cylinder carrying the indicating apparatus. This consisted of an indenting tool, resting upon a piston which fitted into the part of the cylinder nearest to the gun's bore. A small metal cup was inserted into the back of the piston, to guard against any rush of gas past the latter. A flat piece of soft copper was screwed down firmly against the knife-edge of the indenting tool, so that, when the piston was acted upon by the pressure which the exploding powder exerted, the knife was forced into the copper, producing a cut, the dimensions of which were accurately measured, and compared with indentations produced by application of known pressures.

Major Rodman applied this instrument to guns of various calibres up to 11 inches, and instituted several series of experiments, employing in the first instance different natures of cartridges, and afterwards powders of different size of grain, ranging from one to four inches in diameter. The results arrived at presented several anomalies and serious contradictions, but those obtained with the powders of different sizes were, generally, of a nature to warrant a conclusion similar to that arrived at by the late Committee on Gunpowder in the earlier stage of their experiments—namely, that the velocities furnished by small-grain gunpowder may be obtained, with a reduced strain upon the arm, by adapting the size of powder to the calibre of the gun. Major Rodman also fitted this pressure-gauge to a very strong vessel, in which he exploded charges of powder ranging from 700 to 7000 grains, allowing the products to escape through a vent 0·1″ in diameter. The pressure-indications obtained by him varied very greatly; in some they corresponded to 4900 atmospheres (or 32 tons to the square inch), while in the others they ranged as high as 12,400 atmospheres (or 82 tons).

In 1869, the present Committee on Explosive Substances were entrusted by Government with the investigation of the action of gunpowder, which had been taken up by the late Ordnance Select Committee in continuation of the Gunpowder Committee's experiments—the special object of the researches being to ascertain the pressures exercised in guns of different calibres by different descriptions of powder, and to deduce from the results the conditions to be fulfilled by a powder susceptible of safe and efficient employment in very large charges. In their earlier experiments the Committee employed Rodman's pressure-gauge as one method of registering the pressure developed; but the very variable and anomalous results which that instrument furnished led them to devise a modification of it, in which the principal sources of error attending the use of the Rodman gauge appear to have been successfully avoided, and which, under the name of the Crusher gauge, has been since employed throughout the Committee's experiments, in conjunction with another instrument, which will be directly referred to.

The crusher gauge consists of a hollow steel screw-plug, which, like the Rodman gauge, is inserted into holes drilled into the gun at the powder chamber, and at various other parts of the bore. The extremity of the plug nearest the charge is closed by a piston which presses against one end of a soft copper cylinder held by springs in the centre of a small chamber in the plug. The other end of the copper cylinder rests against an anvil. When the gun is fired the piston is pressed against the copper cylinder, and the latter is consequently compressed, thus registering the maximum of force exerted at that particular part of the gun.

The other instrument employed by the Committee is a chronoscope, devised and elaborated by Captain A. Noble, by means of which they have been enabled to determine with ease and precision the time occupied by the projectile in traversing different parts of the bore of a gun. The principle of this instrument consists in registering, by means of electric discharges, upon a recording surface, which travels at a very high and uniform speed, the precise moment when a shot passes certain points in the bore. A series (eight or more) of thin metal disks, 36 inches in circumference, fixed upon one horizontal shaft, are made to revolve very rapidly, by means of a heavy descending weight through a train of multiplying gear.

A stop-clock, which can be connected and disconnected at pleasure with one of the revolving shafts of the machine, serves to determine the precise rate at which the circumferences of the disks revolve. This is about 1200 inches per second, so that one inch represents the 1200th part of a second; and as, by a vernier attached to the instrument for the purpose of reading the results, an inch can easily be divided into 1000 parts, it is evident that the instrument is capable of recording differences of time less than one-millionth part of a second.

Upon the discharge of the gun, which is placed in connection with this instrument, the exact moment when the shot passes a particular point in the bore is recorded on one of the disks during the time that these are revolving at the speed just mentioned. The manner in which this is accomplished is as follows:—At definite distances from each other a number of hollow steel plugs, corresponding to the number of disks of the chronoscope, are screwed into holes drilled in the gun to receive them. Each of these plugs carries, at the end which is screwed in as far as the bore, after the gun is loaded, a steel cutter, which projects very slightly into the bore, and is held in position by a fine insulated wire, having its extremities protruding at the end of the plug, and therefore outside the gun. Each of these wires is then connected with conducting wires which bring it into circuit with a small voltaic battery, and with the primary wire of a volta induction coil, so that, when this arrangement is complete, a distinct voltaic current circulates through each insulated wire in the gun, and through the primary wire of a distinct induction coil. One end of the secondary wire of these coils is connected with the revolving disks, the peripheries of which are covered with strips of white paper coated with lamp-black, and the other end of each secondary wire is connected with a well insulated pointed discharger, there being one of these fixed in front of each disk, with its points adjusted so as to be just clear of the edge of the disk. When the disks are revolving at the full speed, the rate of which is ascertained by means of the stop-clock, the gun is fired, and as the shot rushes past the cutters which project slightly in the bore, it presses each one in succession level with the surface, and thereby causes it to cut the insulated wire. The primary current is consequently interrupted, and the induced current, which is thereby instantaneously developed in the secondary wire of the coil, passes from the particular discharger to the adjacent disk, producing a minute perforation in the paper at the point where it jumps across to the disk, and burning away the lamp-black at that point, so that a readily discernible mark is thus produced. Supposing it possible that all the primary wires could be severed at one and the same moment, then, as the disks are all travelling at the same speed, the spots which mark the discharge of the induced current upon each individual disk would be in exactly corresponding positions, and would therefore form a straight line across the disks; but as they are severed in succession, the series of spots follow each other upon the several disks—the distance between the spot on the one disk and that on the next being small in proportion to the velocity with which the shot has moved from one point to another in the gun.

Some idea is conveyed of the minute intervals of time which are measured by means of this chronoscope, by the fact that the distances between the parts of the 10-inch gun at which the time-records are obtained are in some instances only 2·4 inches, while the total time the projectile takes to reach the muzzle of that gun (a distance of 100 inches) when fired with a battering charge, is about the one-hundredth part of a second.

It will be seen from the foregoing outline of the nature and employment of this instrument, that by its means the time is recorded which the shot occupies, from the commencement of motion, in reaching different parts of the gun's bore; from these time-records are deduced the velocity with which the shot is passing through different parts of the bore, and the pressures in the gun which correspond to the velocities. With the aid of this instrument, and the crusher-gauge employed simultaneously with it, the Committee on Explosives have compared the action in the gun of the powders hitherto used in the service with several gunpowders of foreign manufacture, and particularly with certain descriptions of powder which have been specially manufactured for employment in large charges. Guided by the results obtained, they have succeeded in producing a description of gunpowder (known as "Pebble-powder"), the physical and mechanical characters of which have been so adjusted with reference to one another, that the capabilities of large guns have become more thoroughly developed, and their powers of endurance at the same time much less severely tried, by its employment, than by that of any other descriptions of gunpowder which have been specially devised with those objects in view during the last four years. As regards the size of its pebble-shaped masses, this powder bears great similarity to one of the earlier experimental powders tried by the Gunpowder Committee (in 1859), which served as the starting-point in the development of pellet-powder; but it presents important differences in respect to density, hardness, and uniformity of form of the masses, and it is to the combined influence of these points of difference, in reducing the rapidity with which the pressure is developed in the gun, that pebble-powder owes its efficiency.

A comparison of the results arrived at, by means of the chronoscope and a 10-inch gun, with the powder hitherto used in all rifled cannon, known as R. L. G. powder, with the Russian prismatic powder (which for a time was regarded as superior to all other varieties), and with pebble-powder, at once demonstrates the superiority of the latter. The prismatic powder is shown by these results to light very slowly in the gun, and afterwards to burn rapidly, though not so rapidly as the R. L. G. powder. The slow lighting appears to be due to the fact that the prisms have a very hard and difficultly ignitable coating, which has been produced by the concentration of some of the saltpetre upon the surface of the masses, consequent upon the powder containing when pressed a considerable proportion of water, which, in evaporating, draws the saltpetre towards the exterior of the masses. The subsequent rapid burning of the prismatic powder is due to its comparatively low density. The old R. L. G. is both a rapidly inflammable and a very quick-burning powder when used in large charges, on account of the small size of the particles and their comparatively low density; while the large particles of the dense and comparatively hard pebble-powder light somewhat slowly, and also burn slowly as compared with the others. It should be mentioned that pellet-powder, of comparatively low density, as hitherto made for the service, approaches R. L. G. in the rapidity of its explosion when used in *large* charges, but that, when its density is assimilated to that which has been found most suitable for pebble-powder, it yields results similar to the latter, and there is little doubt that pellet-powder, with this modification, will prove interchangeable with pebble-powder. A comparison of curves, representing the velocities and pressures obtained with pebble, prismatic, and R. L. G. powders, in different parts of the gun, as deduced from the chronoscope results, shows that the velocities of the two first commence by being considerably below that of R. L. G., but that they gradually reach and pass it, the shot leaving the gun at a very considerably higher velocity (that of pebble being the greatest). These curves also exhibit most important differences with regard to the pressure, the maximum being considerably greater with R. L. G. than with the other two, while the area of the pressure is much greater with these than with R. L. G. It should be stated that in experiments instituted with the 10-inch gun, and even with the 12-inch 25-ton gun, the pressures recorded by the *crusher-gauge*, which has been referred to, agree very well with the pressures deduced from the chronoscope results when pebble, prismatic, or pellet powder is used; but that, when R. L. G. or the old L. G. cannon-powder is employed, very considerable and perplexing anomalies are observed, not only between the results of the two methods of experiment, but also between the individual results furnished by the crusher-gauge, applied in one and the same round in different parts of the powder-chambers. These anomalous results have been carefully discussed by Captain A. Noble, in a discourse recently delivered by him at the Royal Institution. The scope of the present Lecture does not permit of a full examination of their probable cause; it may, however, be stated that they appear to be due to a wave-action which is set up in the gases, consequent upon the *vis viva* acquired by these, especially with a rapidly-burning charge, before the shot begins to move in the gun, the *vis viva* being reconverted into pressure at the seat of the shot, and thus giving rise to intense local pressures for exceedingly minute periods of time. It has been shown in the course of the Woolwich experiments that, even with the slow-burning powders, pebble and pellet, when the charge is ignited at the point farthest from the shot, or when the cartridges are greatly increased in length, these intense local pressures, observed with the quick-burning powders, are also developed—a result which is greatly in support of the view that they originate in the *vis viva* acquired by the products of explosion, due to the distance which these travel before they are checked by the shot. An experiment made by Robins, in which he placed a bullet 16 inches away from the ordinary charge in a musket-barrel, and bulged and burst the latter near the seat of the shot by the explosion, leads to the same explanation; and many anomalous results obtained with the Rodman pressure-gauge are obviously also ascribable to the *vis viva* acquired by the gases in the cylinder before they reach the piston which acts upon the cutter at some distance from the bore of the gun.

These somewhat perplexing results have been referred to mainly to show that although great advance has been made in the subject of the adaptation of powder to the ordnance of the present day, much still remains to be done before all conditions are understood which have to be fulfilled in the production of gunpowder thoroughly suited to different guns. There is little question that a powder which is in all respects most suitable for a 7-inch gun will not be equally efficient when applied in a 10-inch gun, and, most probably, the theoretically correct system of meeting the requirements essential to the safe development of the full powers of guns of large size would be the preparation of a special powder for almost every calibre of gun. The practical objections to such a course are, however, obviously insurmountable; hence the result to be aimed at is, the production of a powder which, while fairly utilising the powers of the smaller of our heavy guns, may be safely applied in such charges as are calculated to develop the full value of the largest ordnance.

By the employment of pebble or pellet powder, as now manufactured, not only is the strain upon the guns, up to that of 25 tons, greatly reduced, when velocities equal to those furnished by the R. L. G. powder are attained, but we are, moreover, enabled to obtain from these guns very considerably increased effects without submitting them to a greater strain than they would be exposed to in employing the former service powder to obtain the standard results. But in passing from the 25-ton gun to that of 35 tons, which is designed for a 700 lb. projectile, and a very much heavier powder-charge than has hitherto been used, the satisfactory results furnished by the new powder in other guns are less readily attainable, and it is still uncertain whether, and if so in what way, further modifications in the manufacture will have to be introduced to meet the requirements of the largest guns. The more searchingly the nature of the action of fired gunpowder is investigated, and the more the methods of investigation are varied, the sooner, and the more readily and completely, may we hope to fulfil those conditions in its manufacture which will thoroughly establish its efficiency when applied to ordnance of all calibres. The subject is at present receiving in several quarters the careful study and practical investigation which it merits ; and before passing to other topics which have to be discussed in this section, attention must be briefly directed to a special line of investigation now being pursued by Captain A. Noble, which promises to throw important additional light upon the nature of gunpowder as a propelling agent.

Count Rumford's early attempts to determine the pressure of fired gunpowder by exploding very small charges in a confined space, and experiments of a similar nature instituted some time afterwards by Major Rodman, have already been noticed. The conclusions to which these two experimenters were led by their results, as regards the pressure exerted by gunpowder, differed greatly from each other, and also from the conclusions arrived at in 1857 by Bunsen and Schischkoff, after an elaborate experimental investigation into the nature of the transformation which powder undergoes upon explosion, and of the heat developed when powder is fired in a close chamber. The latter was estimated at 3340° C., or 5980° F., and the pressure which they deduced from their experimental data as the maximum which powder can attain in a closed vessel was about 4374 atmospheres, or about 29 tons in the square inch. This result is no doubt nearer the truth than the estimates made by earlier experimenters; but recent experiments, which will be immediately referred to, appear to have shown conclusively that Bunsen and Schischkoff's estimate of the pressure of fired gunpowder is considerably too low, just as that of Piobert, which is founded upon the assumption that the *solid* products exist as vapour at the time of explosion, and is fixed at about 64 tons (or 9600 atmospheres), is regarded by many as considerably too high. Berthelot, who, like many other of the eminent scientific Parisians, was impelled by the exigencies of the period, during the recent ever-memorable siege of Paris, to devote his energies and talent to subjects of immediate practical importance connected with the defence of that city, has made an elaborate theoretical investigation into the force exerted by different kinds of gunpowder and by other explosive agents. In criticising the deductions made by Bunsen and Schischkoff, from their experiments with regard to the pressure of fired gunpowder, he points out that they have greatly underestimated the latter, because they neglected to take into account the effect of the enormous amount of heat liberated by the compression of the gases when powder is exploded in a confined space; in other words, because the temperature of combustion was calculated upon a volume equal to that of the gases measured at zero and at normal atmospheric pressure, instead of upon *a volume equal to that of the powder itself*, to which volume the gases are obviously condensed when powder is exploded in its own space. He discusses the probable influence, upon the pressure, exerted by the dissociation of the gaseous products of explosion, at the very high temperature developed at the time of their generation; the counteracting influence of the pressure to which the gases are subject; the cooling effect of the expansion of gas while the shot is being propelled from the gun; and the probable consequent continual disengagement of heat, resulting from new chemical combinations which were not compatible with the original high temperature. The estimate which Berthelot is led to form of the pressure of fired gunpowder is not far below that which Rumford arrived at; thus, he gives the pressure of war-powder, exploded in its own space, as 62,700 atmospheres, an estimate about fourteen times greater than that which Bunsen and Schischkoff based their analytical data upon. His conclusions are not as yet borne out by experimental results.

The analytical examination instituted by Bunsen and Schischkoff of the products of explosion of gunpowder dispelled the confidence up to that time entertained in the old theory of the chemical change of gunpowder, which assumed, as already stated, the conversion of the carbon into carbonic acid or carbonic oxide, or both, and the conversion of the sulphur into potassium sulphide. According to their analyses the largest proportion of the sulphur is oxidised to sulphuric acid, potassium-sulphide being one of the smallest products of the change. While there is no doubt that the old theory of the decomposition of powder is very wide of the actual truth, it is generally considered that the method pursued by Bunsen and Schischkoff in burning gunpowder, with the view of collecting the products for analysis, was not calculated to furnish results fairly representing those which would be obtained by exploding gunpowder in a closed vessel, as in the chamber of a gun. Some experiments, subsequently made by Karolyi, in which he exploded very small charges under conditions more nearly approximating to those of the actual employment of gunpowder, furnished analytical results not very greatly at variance with those of Bunsen and Schischkoff, but the value to be attached to them appears likely to be definitely determined before long by the experiments upon which Captain A. Noble is at present engaged. In iron vessels of great strength he explodes, by electric agency, charges of gunpowder ranging up to two pounds; the space in which the charges are fired is varied from that entirely filled by the powder to that in which the latter occupies only ten per cent of the space, and the vessel is fitted with a crusher gauge, by which the maximum pressure developed by the explosion is recorded. The gases are in all instances entirely confined, and are allowed to escape gradually, as soon as expedient, after the explosion, with a view to the measurement of their volume and the collection of portions for analysis (their examination and that of the solid products having been undertaken by myself). It would be premature to enter upon any account of the analytical and other results furnished up to the present time by these experiments; it may be stated, however, that the maximum pressure of fired gunpowder, unrelieved by expansion, has been found to be about 40 tons to the square inch, and that an examination of the relation between the tension and density of the powder-gases, obtained in a closed chamber, furnished results closely corresponding with those deduced from the observation of the tension of gases in the bores of guns, made by the Committee on Explosives.

The imperfect outline which has been given of the investigations, both scientific and practical, which have been instituted during the last two or three years, and are still in progress, will suffice to show that these have not merely an important direct bearing upon requirements which the recent great progress in the construction of artillery has created, but that they are also contributing largely to the attainment of more correct and precise information with regard to the action of gunpowder when exploded in a confined space, and the operation of the various modifying influences which may be brought to bear upon it.

Numerous as have been the attempts during the last sixteen years to apply other explosive agents as substitutes for gunpowder in small-arms and even in artillery, no rival of the latter has yet thoroughly established any good claims to success as a propelling agent, except for sporting purposes. Nor does it appear probable, considering the difficulties which have to be encountered in sufficiently regulating the explosive action of gunpowder to adapt it to the heavy artillery of the present day, that even the apparently most controllable of other explosive bodies—guncotton—will ultimately prove susceptible of safe application in any larger artillery than field-guns. The ultimate failure of the repeated attempts made in Austria to apply guncotton to artillery and small-arms must not, however, be accepted as proof that no results of value are likely to be attained in this direction. A very decided advance had been made towards the successful employment of guncotton in field guns before the Government Committee on Guncotton ceased to exist in 1868; and if the experiments on this subject, which were then suspended, as well as those relating to the employment of guncotton in military small arms, have not been resumed, it is only because the Committee on Explosives, to whom the further investigation of these matters has been entrusted, has hitherto been fully occupied with the more immediately important investigations relating to gunpowder. Some considerable time was devoted by me, about three years ago, to the production of small-arm cartridges of compressed guncotton, suitable for the breech-loading arms of the service, and a system was already at that time pursued with considerable success, of regulating the rapidity of explosion of the material by its impregnation with minute quantities of a non-explosive and otherwise perfectly inert substance, which at the same time imparted considerable water-repellant properties to the cartridge. Experiments with cartridges prepared on this system will be resumed in due course; meanwhile a similar method of treatment has been applied with great success to the production of sporting cartridges made of prepared and lightly compressed guncotton, by Messrs. Prentice, to whose energy and perseverance we are indebted for the firm establishment of guncotton as an important explosive agent.

Although gunpowder is still the only propelling agent susceptible of general application, it no longer enjoys a monopoly in connection with some equally important applications to naval, military, and industrial purposes. The very energetic action of potassium-chlorate upon readily oxidisable substances, and the great rapidity and violence of explosion of mixtures of that class, when compared with similar mixtures containing saltpetre, has given rise for many years past to repeated attempts, often renewed in the same directions, to apply that substance to the production of powerful substitutes for gunpowder. Mixtures of it with resin, powdered nut-galls, and other substances of vegetable nature or origin, have been suggested, and in some instances applied to a limited extent in directions where rapidity and violence of explosive action appear to present advantages, as in some kinds of blasting operations; even the old and well-known mixtures of the chlorate with potassium ferro- and ferricyanide and sugar, which for many years past have been described in chemical handbooks as *white gunpowder*, and *German gunpowder*, have been more than once re-proposed of late, not merely as mining agents, but for use in firearms. The practical objection generally raised, and with reason, against mixtures of this class, that they are of detonating character, and consequently more or less dangerous to transport and handle, is always either met or forestalled by the proposal to keep the ingredients separate until the mixture is actually used, as the violent oxidising property of potassium-chlorate renders the production of powerfully explosive preparations possible by crude and rapidly-performed mixing operations, which would be altogether inadequate for the production of useful explosive mixtures with saltpetre. Such a proceeding is, however, inadmissible in naval and military service, for several reasons; and the trouble which it would involve at the hands of miners using such preparations will probably always lead them to forego any advantages which might result from their employment, and either to adhere to gunpowder or to employ other materials supplied in the form in which they are actually to be used, even though considerable risk of accident may be incurred with these. Some of the preparations of this class, which, disguised by fancy names, occasionally find their way into miners' hands, are of so dangerous a character that it amounts to little short of deliberate criminality to endeavour to find a sale for such materials. Even mixtures consisting chiefly of potassium-chlorate and sulphur have been recently recommended as useful and safe mining agents. It need scarcely be said that a mixture of these substances is liable to explosion if submitted to very slight friction or concussion; and although their sensitiveness to ignition may be very considerably reduced by the admixture of other substances, such mixtures will always be extremely liable to accidental explosion during the process of tamping, or unless handled with very great and constant care. A special application of the mixture of potassium-chlorate and sulphur, which merits brief notice, was made for war-purposes in France at about the time of the late Exhibition. By converting the mixture into a paste, and then drying it, hard masses of the explosive agent can be produced, which are made to fit shells of lead, and afterwards completely enclosed in the metal by the operation of "spinning." A small-arm projectile is thus produced, which may be safely fired from a rifle, but which explodes with fearful violence even upon penetrating flesh, producing the most appalling wounds. It may be remembered that an account was published about a year ago of trials made in London upon horses with explosive bullets of this kind, the results of which established the success of the bullet as one of the most fearful destructive agents ever applied; but the agreement entered into not long before the late war by the principal nations not to employ explosive bullets, has precluded any use being made of this ingenious mode of safely applying so highly detonating a mixture. It need hardly be stated that the conditions essential to safety, which can be readily fulfilled in enclosing a material of this kind in a leaden projectile, and firing it from a small-arm, do not bear comparison with those which arise when shells are fired from guns, even of small calibre.

The discovery of a more violent explosive agent than gunpowder, which may be employed as a charge for shells without any risk of accidental explosion resulting from the concussion to which they are exposed when the gun is fired, has been considered a desideratum for some years past. A few experiments were made by the late Committee on Guncotton upon the employment of that substance in shells, and spherical shells were safely fired from a mortar of 13 inches calibre, but disastrous results were obtained when this material was used as the charge of lead-coated and studded elongated projectiles fired from rifled guns. A few were safely fired, but, without any apparent alteration of conditions, others burst in the gun, and instead of simply indenting and scoring the bore, as would have been the case if a shell charged with powder had burst prematurely, one gun was rendered perfectly unserviceable by the violence of the explosion, and another was burst, the fragments being projected many hundred yards. Further systematic experiments have been continued for Government from time to time, with the view of discovering a safe and powerful explosive agent for shells. The relative disintegrating and scattering powers of a large number of explosive agents has been determined, in the first instance, by filling cast-iron shells of a particular calibre with the different materials; bursting these in a chamber of great strength, lined with wood; carefully collecting all fragments which could afterwards be found on the floor, and which could readily be extracted from the walls of the chambers, and determining the individual and total weights of these. In this way the extent to which the different shells were broken up by the explosion was correctly ascertained, and many explosive agents, for which great power had been claimed, but which proved to be not greatly superior to gunpowder, were eliminated, the most powerful being selected for further experiment. In illustration of the results thus arrived at, it may be stated that, when a shell weighing 16 lb. 1 oz., filled with powder, was burst, all the fragments were readily recovered; they amounted to eighteen, including the plug of the shell, and of these twelve weighed above eight ounces and under two pounds, and only one fragment weighed less than one ounce. Upon bursting a shell of the same kind and weight, filled with a mixture of potassium-chlorate and potassium-picrate, 100 fragments were recovered, and these weighed altogether only 2 lb. 6 oz., nearly 14 lb. of the shell having been dispersed in fragments too minute to be collected individually. Only one of the recovered fragments weighed more than eight ounces, and ninety-three weighed less than one ounce. It need scarcely be stated that such a disintegration of the shell would be far too considerable to render the latter of value as a destructive missile, but the result showed that a small proportion in weight of this potassium-picrate powder, if it could be used in shells, would suffice to produce the desired breaking up of the shell and violent scattering of the fragments, and that therefore the thickness of metal of the shell, and its consequent destructive power, might be very considerably increased. The chilled iron or Palliser shells, which, being of considerable thickness, hold comparatively small charges of powder, would obviously be rendered much more destructive as shells, by substituting for the powder-charges an explosive agent even considerably less violent in its action than the one just cited as an example.

The shell experiments above referred to were followed by a series of another kind, instituted in the first instance for the purpose of determining the relative susceptibility to explosion, by concussion or other mechanical causes, of gunpowder, and of the explosive agents selected from the results of previous experiments as most promising in their nature. These experiments consisted in interposing definite quantities of the materials between flat brass plates, placing them upon a rigid support, and allowing a weight to fall upon them from different heights. It soon became apparent that by varying the weight employed, and the surface and thickness of the layer of explosive material operated upon, some interesting and probably very useful results could be obtained. These experiments have therefore been considerably extended, and I trust shortly to have completed them sufficiently for publication of the results. It should be stated that some similar experiments were instituted by MM. Girard, Millot, and Vogt, during the siege of Paris last year, with mixtures of nitro-glycerine with a variety of solid and liquid substances of inert character, for the purpose of discovering the safest and most suitable media for the application and preservation of that explosive liquid. A communication made at about the same time to the French Academy of Sciences, by M. Champion, on the application to war-purposes of the mixture of nitro-glycerine and siliceous earth, well known as dynamite, contains a statement to the effect that a shell filled with dynamite was safely fired from a gun at Mont Valèrian, and the somewhat hasty conclusion is drawn from this single result that dynamite may be safely used in shells. More conclusively favourable results on the employment of nitro-glycerine in shells were obtained at Shoeburyness three years ago, when six shells (the entire number experimented with) were successfully fired, containing charges of a solid nitro-glycerine preparation, in which a mixture of pulped guncotton and saltpetre is made the vehicle for the employment of the liquid, and which therefore consists entirely of highly explosive material. The power of this substance had been previously demonstrated by numerous experiments, among which a charge less than one-third that of the full powder charge, mixed with sufficient sawdust to fill the chamber of a shell, burst the latter into ten times the number of fragments obtained with gunpowder. Promising as these results were, it was deemed advisable to seek for some other explosive agent than a nitro-glycerine preparation as the material for shell-charges, for two reasons—firstly, because the well-grounded confidence in the safety of nitro-glycerine and its preparations, essential to their employment in naval and military service, does not yet exist; and, secondly, because the explosive force of these preparations, as illustrated by the one experimented with, appeared considerably to exceed that required in connection with the most general application of shells. Eventually, one of the salts of trinitrophenic acid or picric acid was found to furnish an explosive mixture, which, as far as experiments have been carried, has proved to possess all the essential qualifications of a material applicable in the service as "shell-powder."

Picric acid, or carbazotic acid, as it was first called, is one of the earliest explosive substances of organic origin known, having been discovered as far back as 1788. It is produced by the action of nitric acid on a variety of organic substances. One of the earlier methods of obtaining it readily was by the action of nitric acid on indigo; but a comparatively abundant source of it was pointed out about thirteen years ago by Stenhouse, who readily produced it in large quantities by acting with nitric acid upon the resin of "Xanthorrhœa saxtilis," which was imported in considerable quantities from Botany Bay. Since the manufacture of phenol or carbolic acid from coal-tar has become developed, picric acid has been very extensively produced from that substance, and, as a cheap and brilliant yellow dye, has become an important article of commerce.

The acid itself does not explode, but burns quickly with a bright flame; its salts are all more or less powerfully explosive, and detonate when struck. The potassium salt is that most easily prepared, on account of its very slight solubility in water. It is also one of the most highly explosive. When mixed with oxidising agents, and especially with potassium-chlorate, it furnishes very powerful explosive materials; indeed, the chlorate mixture approaches nitro-glycerine and gun-cotton more nearly in violence of action than any other explosive agent produceable on a practical scale. This mixture is, however, so susceptible of detonation by friction or concussion as not merely to render its employment in shells impossible, but also to preclude its application to any purpose without the adoption of very special precautions. Other mixtures containing potassium-picrate have been made the subject of experiment, especially in Paris, where so-called "*poudre picrate*" or *poudre Designolle*, composed of potassium-chlorate, potassium-picrate, charcoal, and saltpetre, was prepared and experimented with upon a considerable scale about three years ago, as a substitute for gunpowder in firearms, and for other purposes. A fearful accident at a factory in Paris, where large quantities of the potassium-picrate were manufactured, led to the abandonment of these experiments; but there appears little doubt that picrate preparations were included among the agents of destruction employed by the Communists in the recent struggle at Paris. In the course of the experiments with shells containing various explosive substances, to which reference has just now been made, I was led to examine the properties of mixtures of ammonium-picrate with oxidising agents. This picric compound, which may be readily prepared upon a large scale, differs importantly in its behaviour, when exposed to heat, from the potassium-picrate, and from several other salts of this acid. When heated over a flame it fuses, sublimes, and burns without any tendency to explosion, while the potassium salt detonates under the same conditions. The latter also detonates somewhat violently when submitted to a moderate blow, whilst it is difficult to obtain evidence of detonation of the ammonium salt when struck sharply and repeatedly. A mixture of the potassium salt with saltpetre, though less susceptible to explosion by a slight blow than the chlorate mixture, is yet powerfully detonating; while a mixture of ammonium-picrate and saltpetre requires a violent blow to develop slight and partial detonation, and exhibits no tendency to ignition when submitted to very severe friction, which would at once explode the least sensitive of the explosive mixtures proposed as substitutes for powder. When flame is applied to particles of the mixture of saltpetre and the ammonium salt (to which I have given the distinctive name "picric powder"), the individual particles deflagrate with a hissing sound like that of the sudden escape of steam, and the deflagration has little or no tendency to spread to contiguous particles; but if the mixture is strongly confined, as in shells, it explodes violently, and exerts a destructive action, less formidable than that of guncotton, nitro-glycerine preparations, and potassium-picrate powder, but considerably greater than that of gunpowder, and therefore likely to prove a valuable substitute for the latter when greater violence of action is desired with shells of small capacity. A number of shells charged with picric powder have been fired without a single casualty from guns of different calibres, ranging to the 9-inch gun with the employment of a battering charge of 43 lb. of R. L. G. powder. The safety of this substance is therefore considered sufficiently established to warrant the institution of thorough trials of its powers as an explosive agent for shells. It is a curious and important circumstance connected with this mixture, that though ammonium-picrate and potassium-nitrate undergo mutual decomposition, with production of the deliquescent ammonium-nitrate, if the two be *dissolved* together in water, the addition of sufficient water even thoroughly to moisten the mixture appears to induce no such change, as the latter, when dried again, has no increased tendency to absorb moisture from the air, which it scarcely does to the same extent as gunpowder. The picric powder is therefore quite equal in permanence to gunpowder, and as water may be used in incorporating the ingredients without any detriment to the stability of the mixture, its preparation is, at any rate, not more dangerous than the manufacture of gunpowder, and it may be safely submitted to the pressing and granulating processes which are applied to the latter. As, moreover, the cost of picric powder, as compared to its power, is not considerable, this explosive agent is now recognised as susceptible of advantageous application to service purposes, provided its sufficient superiority over powder in regard to violence of action is satisfactorily established. It should be stated that, some time after experiments had been in progress with this material, at my instigation, it came to my notice that a Frenchman, M. Brugère, had been also experimenting with mixtures containing ammonium-picrate, and had suggested the employment of a saltpetre-mixture as a general substitute for gunpowder. It does not appear that any steps were taken in France at the time to submit this proposal to practical test; and there is good reason to believe that, as regards naval and military uses, the picric powder is hardly likely to offer special advantages, excepting as a safe material for use in shells.

The successful application of the remarkable explosive liquid, *nitro-glycerine,* which is primarily due to the ingenuity and untiring perseverance of Mr. Alfred Nobel, and which has been developed chiefly within the last seven years, presents several points of great interest. Though this liquid was discovered as far back as 1847, Nobel was the first to attempt its practical application. His original proposal to apply it in conjunction with gunpowder (*i.e.* that of adding to the explosive force of the latter when used in shells, and for mining purposes, by impregnating the grains with the highly-explosive liquid) was not attended by any tangible success. He then appears to have proceeded upon the idea that by raising some small portion of a charge of nitro-glycerine to a temperature sufficiently high for its violent decomposition, he might succeed in producing an initiative explosion of that part of the charge, which would be transmitted to the remainder, and he was thus eventually led to employ a small charge of a detonating material, such as percussion-cap composition, to bring about the violent explosion of the liquid. This ingenious expedient, the precise rationale of which I had afterwards occasion to investigate in its general application to the development of the action of explosive substances, was the foundation of the successful employment of nitro-glycerine in mining operations. The existence of several most serious obstacles to the use of nitro-glycerine in its pure liquid condition was, however, soon practically demonstrated,—in several instances, indeed, by most disastrous accidents, not easily effaced from memory, and the ingenuity of Mr. Nobel was consequently taxed to devise some method of promoting safety, and also certainty of action, in the employment of this powerful explosive agent. These ends were attained, at any rate to a great extent, by mixing nitro-glycerine with some solid substance of perfectly inert nature, and of absorbent character, through the medium of which the liquid is susceptible of employment in a condition assimilating to that of other explosive agents in practical use. The vehicle employed by Nobel is a light siliceous earth, known in Germany as "kieselguhr," which may be mixed with about three times its weight of nitro-glycerine without becoming more than moist to the touch, and is therefore readily susceptible of manipulation as a solid material. This mixture, to which the name of *Dynamite* was given by Nobel, is also specified to contain a small proportion of alkaline matter, to be added for the purpose of counteracting any tendency to the spontaneous development of free acid in the nitro-glycerine. Dynamite is as readily susceptible of explosion through the initiative agency of a detonating fuze as nitro-glycerine itself; and though it obviously cannot be so powerful an explosive agent as that substance when successfully applied in its undiluted condition, its destructive powers are still very greatly in excess of those of gunpowder; and this fact, together with the circumstance that, when properly applied, it does not need confinement for the development of its explosive force, and that it may be employed, with certain precautions, in damp blastholes, without great detriment to its action, has led to its gradually becoming very extensively applied to industrial purposes. Certain defects are inherent in the material, such as its losing its susceptibility to detonation by the ordinary means at a low temperature, and the tendency of the nitro-glycerine to partial separation from the siliceous earth during transport and storage; but, in balancing its advantages against those of other explosive agents, the special defects of these have also to be taken into account; so that, provided the uniform stability of the material becomes firmly established, and the apprehensions as to its comparatively dangerous character, to which certain accidents have given rise, are allayed by further experience in its storage and use, and possibly by improvements in its manufacture, a high position may be assigned to dynamite among the most useful explosive agents of the present time.

Several other methods of applying nitro-glycerine as a destructive agent have been brought to public notice since Nobel's dynamite first attracted attention. Among the proposed preparations, the most recent, and one for which special power and virtues have been claimed, is the substance to which its inventor, M. Engels, has given the name of *Lithofracteur*, and which contains, in addition to nitro-glycerine and an absorbing medium of the description used in dynamite, some proportion of other explosive materials (such, for example, as the constituents of gunpowder). This substance, which appears to have been applied to a limited extent by the Prussians during the recent war, is of a plastic and almost pasty nature, and is employed in the form of rolls made up in paper, which absorbs some proportion of the nitro-glycerine. Its tendency to yield to pressure, even when suddenly applied, renders its accidental explosion by mechanical force a matter of very considerable difficulty, probably more so than in the case of dynamite. As regards its claims to superiority in point of safety and power over the latter and other similar preparations, they are still matters of dispute, and their validity can only be satisfactorily determined by careful comparative experiment.

During the siege of Paris a dynamite factory was established in the outskirts of the city, and, in the absence of the particular siliceous earth which Nobel employs in its preparation, MM. Girard, Millot, and Vogt made a series of experiments, already alluded to in this Lecture, with the view of ascertaining what substance could be best employed as a substitute for that absorbent material; their results indicated that, in addition to precipitated silica, the best media to be used are kaoline, tripoli, alumina, or sugar, the latter presenting the special feature that the nitro-glycerine can be rapidly separated from it by addition of water, a supposed advantage which Mr. Horsley had previously claimed for a mixture of nitro-glycerine and alum, but which may obviously constitute an important disadvantage in special applications of these mixtures—the tendency to separation of the liquid nitro-glycerine from them in wet blast-holes being a decided defect.

Sawdust and similar absorbent materials have also been used as vehicles for the application of nitro-glycerine, especially in America, under the name of *Dualine*; and another preparation of nitro-glycerine, to which some years ago I gave the name *Glyoxiline*, and with which some very effective blasting and engineering operations were carried out, consists, as already stated, of a mixture of guncotton pulp and saltpetre, which is saturated with nitro-glycerine. In the preparation of this material, one of the objections to the use of nitro-glycerine, arising out of its poisonous nature, and the readiness with which it is absorbed into the system, was at any rate partially met by providing the granules or masses of glyoxiline with a coating of some impermeable material. The injurious effects of nitro-glycerine upon the health of those constantly handling and employing it or its preparations, must unquestionably be frequently productive of serious results, but are scarcely likely to interfere with their industrial applications, as it is well known that risk of accident or of permanent injury to health will not deter men from persevering in the continuous use of means which may add to the productiveness of their labour.

The meeting of the British Association in 1862 marks the period when guncotton, which fell into disfavour in England and France within two years of its discovery by Schönbein in 1846, again attracted public attention in this country. A committee was appointed at the Cambridge meeting to report on the system of manufacturing and applying guncotton, which had been elaborated in Austria by Baron von Lenk; and, early in the year following, Her Majesty's Government received from that of Austria a confidential communication of the full details respecting Von Lenk's improvements. I was at once called upon, in the spring of 1863, to investigate practically and scientifically the merits of the several modifications which had been imported into the original process of manufacture, as laid down by Schönbein; and, early in the year following, a committee was appointed by the Secretary of State for War, under the presidency of Sir Edward Sabine (and including several members of the British Association Committee), with instructious "to investigate the properties of guncotton as a substitute for gunpowder." The continuance of the chemical and manufacturing portion of these investigations being left in my hands, as a member of that committee, the results arrived at with regard to the production and composition of guncotton, the causes to which the uncertain stability hitherto exhibited by it were to be ascribed, and the extent to which Von Lenk's improvements had removed or reduced these, were communicated by me from time to time to the Committee and the Royal Society. Some very searching experiments were made upon a considerable scale, for the Committee, with guncotton manufactured according to Von Lenk's process, at Waltham Abbey, with a view to ascertain whether the requisite confidence could be placed in its keeping qualities, and the results were so far satisfactory, that the Committee, in the Report which they submitted in 1868, were enabled to state that strong evidence had been afforded of the stability of the material when properly manufactured; though they considered that further experience was required to determine this important point with sufficient certainty to justify a general adoption of guncotton for military service. The various samples of guncotton upon which the Committee based their conclusions in 1868 have been preserved to the present day, under the same conditions; recent inspection has shown them to be quite unaltered. A further experience of more than three years has therefore been acquired, favourable to the stability of the material, most of which was manufactured eight and seven years ago. With regard to the methods of preparing guncotton for mining purposes, and for artillery and small-arms, devised by Von Lenk, which have been described in detail to the British Association at former meetings, the results arrived at by the Committee did not sufficiently bear out the expectations which at first were entertained of the practical value of those methods, to warrant any decisive conclusion of a favourable nature being arrived at; and it was obvious that much remained to be done to obtain proper control over the explosive power of guncotton, and to render it really susceptible of being safely and beneficially substituted for gunpowder.

In examining the results obtained when guncotton was fired under pressure (*i.e.* in confined spaces), and observing the very limited and uncertain extent to which the explosive violence of the material was subjected to regulation, under those circumstances, by the methods of twisting and winding, and other expedients employed by Von Lenk to give compactness to a charge of the fibrous material, I was led to believe that there would be much greater prospect of attaining the desired results if guncotton could be converted into a form readily susceptible of treatment by compression, so as to furnish perfectly homogeneous masses of required form and density,—resembling gunpowder, in fact, in their physical character. This object was attained by submitting the guncotton fibre to the pulping process applied in the preparations of rags and fibres for paper-making, and afterwards converting the pulp into sheets or moulded masses, to which perfect compactness and a high density could be given without difficulty, by means of well-known mechanical appliances.

This modification of the method of preparing guncotton, when applied to the preparation not only of mining charges, but also of cartridges for small-arms and for artillery of small calibre, soon furnished decisive and very promising results. The experiments hitherto instituted with compressed guncotton in small arms and artillery have been only of preliminary nature, as already stated; but the substitution of charges of compressed guncotton for blasting and mining operations, in place of the guncotton rope hitherto employed, was not only at once productive of greatly improved results on account of the considerable reduction effected in the size of the charges of a given weight, but also imparted to the material a character of safety (in its storage, and all manipulations with it) which it did not hitherto possess, as the masses of compressed guncotton cannot be made to explode by accidental ignition unless they are very strongly confined. The advantages resulting from the application of the pulping process to guncotton were, however, not limited to the improvements effected in its efficiency as an explosive agent, but extended, with a degree of importance scarcely at first anticipated, to the properties of the material, specially in regard to stability, and to its manufacture, which was speedily quite revolutionised thereby. Thus, instead of the raw cotton of high quality and long staple, which it had been necessary to use in carrying out the Austrian system, any description of cotton could be employed, and the waste cuttings from spinning-machines (such as are used for cleaning machinery) proved to be as suitable as cotton in any other form.

The purification of the raw cotton from seed and from other matters foreign to cellulose, which are contained in the hollow fibres, constituted a most important preliminary operation in the Austrian process. Even by a searching treatment with alkali, and careful washing, these impurities were never thoroughly removed; and the products of somewhat indefinite and comparatively unstable nature, produced by the action of the acids upon these traces of organic impurities, and occasionally remaining in the finished guncotton, were clearly shown, in the investigations which I carried out on the stability of this substance, to be the starting-point in any change which guncotton might sustain by long exposure to elevated temperatures. The cotton-waste now used in making guncotton has undergone so thorough a purification by the various manufacturing processes through which it has passed, that, while no further preliminary purification is requisite, the finished guncotton obtained from it is practically free from the impurities just referred to.

The cotton having been treated with the mixed nitric and sulphuric acids, and the greater portion of the acids afterwards separated, the subsequent processes of purification and preparation differ entirely from those pursued in Von Lenk's system. The purifying processes prescribed by the latter, and demonstrated experimentally to be absolutely essential in dealing with guncotton in the form of fibre, consisted in very long-continued washing (extending over several weeks) in running water, and subsequent

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treatment with alkali. The capillarity of the long fibres constituted the great obstacle to rapid purification, the displacement of the acid from the interior of these being obviously a very slow operation. In the present system of manufacture the guncotton is rinsed two or three times in a large volume of water, the latter being extracted as completely as possible between each rinsing by means of centrifugal apparatus; it is then transferred to a rag-engine of the kind ordinarily used in producing pulp for papermaking. Here it is not only reduced to the state of fine division necessary for its subsequent conversion into homogeneous compressed masses, but it also undergoes at the same time a most searching purification, which is continued in a still more complete manner in the next operation, the pulp being transferred to what is technically called a poaching-engine, where it is beaten about so as to remain uniformly suspended in a large volume of warm water, continuously renewed, and rendered slightly alkaline at the close of the operation. This washing is carried on uninterruptedly until samples of the material under treatment have satisfactorily sustained a very severe heat-test, and generally lasts about 48 hours. At least 10 cwt. of guncotton are washed at one time in the poaching machine; in this way an exceedingly intimate mixture of the products of many dipping operations is obtained, and any fluctuations in the composition of the guncotton are thus made to counterbalance each other, much greater uniformity in the explosive power of the product being obviously secured than was previously attainable. When the guncotton pulp is completely purified it is converted into compact masses of the desired forms and density by a preliminary moulding process, and subsequent application of hydraulic pressure ranging from 4 to 6 tons upon the square inch. During the whole of these manufacturing operations the guncotton is wet, and therefore absolutely uninflammable. Even when it leaves the presses it still contains about 20 per cent of water, and is so perfectly safe in this condition that slabs of it may be cut up by means of circular or band saws, revolving very rapidly, and holes drilled in it by drilling machines, or even by means of a red-hot iron. In this damp and incombustible condition the compressed guncotton may be stored in water-tight cases for any length of time; the final drying of the masses is carried on very rapidly and safely upon hot plates, which are freely open to the air at the sides.

Numerous experiments, on a considerable scale, have been made with a view to thoroughly test the safety of compressed guncotton. Deal boxes, filled with the material in the ordinary way in which it is stored, and securely closed, have been arranged in piles, and the contents of a box in the centre of the pile have been ignited by means of a fuze. In another experiment one of the inner boxes of a pile has been surrounded by highly combustible material, and the latter inflamed, so as to envelop the box in fire. In all instances the contents of the one box have ultimately burnt, but without even shattering the latter, and the large volume of flame produced for a few moments sometimes penetrated to the interior of another box in the heap, causing its contents to inflame in like manner; but in no instance was an explosion produced. Those boxes the contents of which were intact were removed from the pile without incurring any danger, although the inflamed boxes were still burning. Closed boxes, filled with compressed guncotton, have been fired at with a Martini-Henry rifle from a distance of 100 yards; in some instances the box and contents were perforated by the bullet without igniting the guncotton, in other instances the contents were inflamed, but no explosion occurred. Numerous other practical proofs have been obtained of the safety of compressed guncotton as compared with gunpowder, and with guncotton in the comparatively loose and open condition.

When the Austrian improvements in the preparation of guncotton were communicated to the British Association in 1864, great stress was laid upon the fact that the proper development of its explosive force could only be effected by confining the material in receptacles of considerable strength, as in shells, in firmly tamped bore-holes, or very strong cases of wood and metal. In attempts made by our Royal Engineers in the autumn of 1863 to apply guncotton to the demolition of the works at Corfu, the operations failed, in the majority of instances, to furnish any satisfactory results, evidently on account of deficiency in strength of the cases, specially constructed for this purpose, in which the charges of guncotton were supplied by the Austrian Government. These, and other unfavourable results, warranted the conclusion that guncotton could not be advantageously applied as a substitute for gunpowder in connection with military operations of mining and demolition which it is desirable to be able to accomplish hastily, and for which consequently few men and appliances, and little preparation, should be needed.

The discovery made in 1864, by Mr. Alfred Nobel, that the explosive force of nitro-glycerine can be fully developed without any strong confinement of the charge, through the agency of a detonation, appeared to give that substance so great and well-founded a claim to superiority over guncotton and other explosive agents, in connection with some of their applications, that the pre-eminence which this liquid enjoyed for a time as an explosive substance of quite exceptional properties, almost equalled the dread of its dangerous character inspired by the succession of fearful accidents which inaugurated its employment on an extensive scale. Not long afterwards, however, it occurred to my assistant, Mr. E. O. Brown, to try whether compressed guncotton could not also be violently exploded in the open air, through the agency of a detonation, and a result was obtained quite similar to that furnished by nitro-glycerine. I was led by this observation to institute a systematic experimental inquiry, with the view of throwing light upon the nature and cause of the remarkable phenomena exhibited by these two bodies, and I soon found that *all* explosive compounds and mixtures, even down to gunpowder, are susceptible of violent explosion by means of a detonation, though the nature and force of the required detonation vary very considerably with different explosive substances. The results arrived at by a careful inquiry into the conditions to be fulfilled in determining the detonation in open air of these compounds and mixtures, and of the operating causes, physical and mechanical, which tend to modify the character of the phenomena produced upon their exposure to heat, concussion, etc., are detailed in the Transactions of the Royal Society—their present discussion is precluded by the great length which this Lecture has attained. It may, however, be stated in general terms, that although the amount of mechanical force developed by the initiative detonation, and the suddenness of its operation, play most important parts in determining the violently sudden metamorphosis of the substance submitted to their influence, neither the severity nor suddenness of the blow or concussion, nor the heat developed by it, nor the peculiar nature or comparative instability of the particular explosive body operated upon, suffice individually or collectively to account for all the several phenomena of detonation; but that some yet unexplained peculiarity in the initiative concussion employed, and probably some physical relation or antagonism between it and the particular concussion produced by explosion of the substance operated upon, must in many instances contribute to produce results, positive and negative, which cannot be satisfactorily explained by simple reference to the operation of mechanical force, and consequently of heat. In illustration of this it may be instructive to give two examples. The detonation of compressed guncotton is accomplished by the explosion of 0·32 grm. (5 grains) of confined mercuric fulminate, placed in contact with the mass, but it requires ten times that quantity of the violent explosive agent, chloride of nitrogen, also confined, to produce the same result. Again, the mechanical force exerted by the explosion of nitro-glycerine is fully equal to that developed by the mercuric fulminate, yet a quantity of nitro-glycerine, about seventy times greater than the minimum of the fulminate required to detonate compressed guncotton, fails, when exploded in contact with the latter, to produce any other result than the complete mechanical disintegration of the mass.

With regard to the general manner in which a detonation action determines the violent explosion or sudden chemical disintegration of such a substance as guncotton, the similarity of its operation to that of a blow is readily demonstrated by many and simple experiments, for a description of which I must refer to my paper presented to the Royal Society in 1869; one or two may, however, be mentioned, which have been made with guncotton, and which probably illustrate the subject sufficiently for present purposes. The heat developed in a mass, when submitted to a blow, depends upon the resistance which its particles oppose (by reason of its rigidity or solidity) to the motion of the body striking it. Repeated blows may be required to explode a detonating substance placed in the form of loose powder upon an anvil; the force being, at first, in part expended in compressing the particles into a compact mass. When no longer free to move, the resistance they oppose to the force applied determines the sudden transformation of the latter into heat to a sufficient extent to bring about the detonation of the substance struck. If, in the case of guncotton, the force developed by a detonation, even of a powerful character, is allowed to operate upon the material in a loose flocculent condition, the latter is simply dispersed; again, if the guncotton be only lightly compressed, a much more powerful detonation is required for its explosion than if it be in a very compact condition; and if the mass of the highly compressed material be only very small, it cannot be detonated by the means which are successful with larger masses, unless special precautions be taken, by fixing it rigidly to the detonating fuze, to prevent its being dispersed by the force which the explosion of the latter exerts. These facts, when compared with the following experiments, demonstrate that the action of a detonation in developing the violent explosion of the substance upon which it is allowed to operate, is that of a very sudden blow given to some portion of a mass, the particles of which are in a condition to resist the motive or dispersive power of the mechanical force applied. A bullet from a Martini-Henry rifle was fired at a distance of about

50 yards, against a slab of compressed guncotton, 0·75 inch thick and 3·75 inches in diameter (weighing four ounces), freely suspended in air by a string: the guncotton was simply perforated by the bullet. A similar result was several times obtained with slabs of guncotton of the same dimensions, and with others double the thickness. On making the experiment with a slab of three times the thickness, the guncotton was inflamed but not detonated by the impact of the bullet. The mass was in this instance of sufficient thickness to offer considerable resistance to the penetrative power of the bullet; the passage of the latter was therefore retarded to such an extent as to give rise to the heating of the opposing guncotton-particles up to their inflaming point. This experiment was repeated with the same result, but when a bullet was fired against a piece of compressed guncotton four times the thickness of that first employed, and weighing one pound, the result was detonation of the mass.

It need scarcely be stated that the detonation of a large quantity of an explosive body is accomplished by the initiative detonation of a very small portion of the mass; this is the case even if the material is arranged in the form of a train of considerable length, the detonating fuze being applied at one extremity. Rows of guncotton disks from three to five feet in length, with intervals of 0·5 inch and 1 inch between the individual masses, have been detonated in this way. There is, however, a limit to the distance to which a detonation will be transmitted along a row of spaced disks, the limit being determined by the particular weight of the masses employed; if it be exceeded, those masses which are at the farther extremity will be inflamed and scattered, instead of being detonated. A few preliminary experiments have been made with the view of determining, by means of the chronoscope, the rapidity with which detonation progresses along a row of guncotton disks. This will no doubt vary with the sizes of the masses: in an experiment with disks weighing two ounces each, placed in a row without intervals, it was found that the detonation extended to three feet in about one five-thousandth part of a second.

Time will not permit of the discussion of many other points of scientific interest connected with the detonation of compressed guncotton and of other explosive agents, but it will probably prove interesting if a few illustrations are furnished, in conclusion, of the practical value of this mode of developing the force of explosive agents.

The necessity for confining gunpowder and other explosive materials in strong receptacles, for the purpose of developing their explosive force, is greatly reduced, and is, indeed, entirely dispensed with in the case of charges fired under water, when detonating fuzes are used as the exploding agents. Thus, if a quantity of gunpowder which, when enclosed in a strong iron receptacle, will be completely exploded, producing a particular destructive effect when fired in the ordinary way, is confined in a thin glass vessel, or in a bag of waterproof material, the receptacle will be burst open upon the first ignition of the charge, and a large amount of the powder will be dispersed in the water; but if a detonating fuze be employed to fire the charge contained in the thin envelope, the powder will be completely exploded, the destructive effect produced being at least as great as that of the charge fired in the strong vessel by the ordinary method. This result is of very great importance, because, in employing submerged charges of gunpowder or other explosive agents for purposes of demolition, or as submarine mines for war-purposes, it is no longer necessary to use very strong and cumbrous receptacles for the purpose of obtaining the desired result; their strength need only be sufficient to insure the perfect exclusion by them of water from the charge at the depth of immersion at which it has been employed. In the recent demolition of the wreck of the "Golden Fleece," off Cardiff, by the Royal Engineers, large charges (500 lb.) of gunpowder were simply enclosed in waterproof bags and exploded with detonating fuzes. The results produced with these were quite equal to those obtained with similar charges enclosed in strong iron cases.

Masses of hard material, of great size or strength, such as blocks of hard rock, large iron castings, or thick bars of wrought iron, may be broken up by simply placing upon one of their surfaces a comparatively small charge, quite unconfined, of compressed guncotton, or of a nitro-glycerine preparation, and exploding it by means of a detonating fuze. In such operations it is obvious that the destructive effect of the detonation will be increased by covering the charge to be exploded by sand or other material, which will act as tamping; but, in hurried operations, results may be obtained with either of the materials specified, by detonating them when freely exposed to air, which could not have been produced by previously known modes of using explosive materials. The demolition of stockades, bridges, and other structures, which it may be desirable to destroy or render useless as expeditiously as possible, in the course of military operations, may also be effected with much greater ease, rapidity, and certainty, by the aid of detonation, than by the old method of operation; and the ease and safety with which compressed guncotton may be applied to these purposes has been demonstrated by numerous experiments instituted by the Royal Engineers. In mining and quarrying operations, the process of hard tamping, which is indispensable in connection with the ordinary method of blasting, may be dispensed with by application of guncotton and of nitroglycerine preparations, which are more readily exploded, with full destructive effect, by detonation, than other explosive materials at present known. A laborious and often very hazardous operation may thus be dispensed with.

For the hasty demolition of buildings, and of military works, such as casemates, magazines, or forts, the explosion by detonation affords most important facilities, reducing the difficulties, danger, and cost, of such operation, to a minimum. Some results obtained in this direction by the Royal Engineers with compressed guncotton may be quoted in illustration of this. It was desired to destroy a counterscarp gallery (forming part of the old works at Portsmouth), which was 250 feet long and 7 feet wide. Its front wall was from 5 feet to 5 feet 9 inches thick, and was pierced with nineteen loopholes. It was roofed over by an arch 18 inches thick (from over which the earth had been removed), and its total internal height was 7 feet 4 inches. At either end there was an opening, closed by a wooden door, which was protected by an iron grating composed of one-inch bars, 4 inches apart. It was proposed to submit this counterscarp to a succession of small experiments, and, in the absence of any experience of the effects of guncotton applied in the interior of a building, it was decided to suspend 60 lb. against the wall, under the haunch of the arch, placing them in three charges near one extremity of the gallery. The simultaneous detonation of these charges accomplished the destruction of about 140 feet of the gallery—about 114 feet being actually demolished. But this was only part of the damage produced. The violent concussion at the other end of the gallery, where the column of gas was checked in its escape, occasioned the destruction of about 80 feet of this part of the counterscarp, and the bars of the iron grating, by which the exit was closed, were bent and twisted into fantastic shapes, and hurled to a distance of about 60 yards. This long gallery was thus rendered entirely useless, and the greater part of it destroyed, by the detonation of 60 lb. of compressed guncotton; and there is little doubt that, had the same quantity been lodged in the centre instead of at one end, the gallery would have been completely demolished.

Another illustration of the simple, rapid, and effectual manner in which the demolition of structures of great strength may be accomplished by the detonation of compressed guncotton, was furnished by the destruction of a Martello tower near Rye. This structure, of circular form, was built of brick, the wall being 12 feet thick on the sea side, and tapering to 7 feet 6 inches on the land side. It had two window openings, and one door opening, and its cubical contents were 7600 cubic feet. On the basement of this tower 200 lb. of compressed guncotton were placed in three piles, freely exposed, which were arranged to be fired simultaneously. Their explosion caused the upper portion of the tower, with the roof, to rise gently a few feet in the air; the walls turned over, outwards, and the upper part subsided to the ground; the demolition of the tower being most complete, while not a brick was projected 50 yards from the spot. The entire operation was accomplished by two or three persons, within one hour of their appearing upon the ground. A second tower was subsequently demolished with 184 lb. of guncotton, with similar results. It was calculated, from existing data, that at least 1200 lb. of gunpowder must have been employed to produce similar results.

In this sketch of the recent progress which has been made in the application of explosive substances, many points of interest and importance have unavoidably been passed over; sufficient, however, will have been said to show not only that the production and utilisation of these powerful agents of destruction, and these indispensable auxiliaries in the development of industrial resources, have been advanced in an unprecedented manner within the last few years, but also that very much remains to be learned regarding their nature and operation, and the conditions to be fulfilled in their most efficient application in many important directions.

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